Int J Adv Manuf Technol (2008) 38:441–446
DOI 10.1007/s00170-007-1114-9

ORIGINAL ARTICLE

On the finite element modelling of high speed hard turning

A. G. Mamalis · J. Kundrák · A. Markopoulos · D. E. Manolakos

Received: 7 November 2006 / Accepted: 25 May 2007 / Published online: 14 August 2007

Abstract The results reported in this paper pertain to the simulation of high speed hard turning when using the finite element method. In recent years high speed hard turning has emerged as a very advantageous machining process for cutting hardened steels. Among the advantages of this modern turning operation are final product quality, reduced machining time, lower cost and environmentally friendly characteristics. For the finite element modelling a commercial programme, namely the Third Wave Systems AdvantEdge, was used. This programme is specially designed for simulating cutting operations, offering to the user many designing and analysis tools. In the present analysis orthogonal cutting models are proposed, taking several processing parameters into account; the models are validated with experimental results from the relevant literature and discussed. Additionally, oblique cutting models of high speed hard turning are constructed and discussed. From the reported results useful conclusions may be drawn and it can be stated that the proposed models can be used for industrial application.

Keywords Machining · Finite element method · Hard turning

A. G. Mamalis (✉) · A. Markopoulos · D. E. Manolakos
Manufacturing Technology Division,
National Technical University of Athens,
Athens, Greece
e-mail: mamalis@central.ntua.gr

J. Kundrák
Department of Production Engineering, University of Miskolc,
Miskolc, Hungary

1 Introduction

Hard turning, a machining operation used for the processing of hard materials such as hardened steels, has been brought into the forefront of modern metal cutting operations with the increasing demand for manufacturing high quality components, e.g., gears, shafts, bearings, dies and tools, from these kinds of materials. Cutting tools employed in hard turning are made of specialized tool materials, such as cubic boron nitrite (CBN), that are able to overcome the problems experienced during the process [1]. These cutting tools are ideal for machining iron-based materials at the severe cutting conditions associated with hard turning; they possess exquisite properties, even at elevated temperatures, allowing for their application at high cutting speeds and without the use of any cutting fluids [2]; by dry cutting not only environmentally-friendly characteristics are attributed to the process, but also cost reduction can be attained by omitting buying and disposal costs of the cutting fluids [3–5]. In addition the combination of hard turning and high speed machining is proved to be very advantageous since a great reduction in processing time can be achieved [1].

Hard turning is very advantageous for a wide spectrum of applications and is also considered as an alternative for a variety of processes, since the single-step superfinish hard turning can replace the abrasive processes, traditionally used as finishing operations, or non-traditional processes, such as electrical discharge machining (EDM), in machining hard parts, offering accuracy equal to or better than that provided so far, flexibility and considerable machining time and cost reduction [4–7].

Note, however, that hard turning has not been introduced into modern industry as much as it should be, mainly because of phenomena such as rapid tool wear or cracking and chipping of the cutting edge due to extreme pressure and temperature imposed on the cutting tool, which lead to poor machining results [8]. Furthermore, as a novel machining process, it needs to be further studied so that it may be optimized. Most research work is limited to experimental results, but, also, the modelling of hard turning can provide useful data to better understanding the process. Numerical modelling and, especially, the finite element method (FEM) have been widely used in the past for the analysis and the prediction of the cutting performance in machining operations. FEM has been a very powerful tool in the cutting technology and can be applied to high speed hard turning as well.

In the present paper FEM is employed in order to simulate dry high speed hard turning, investigating the influence of the cutting speed on the performance of the cutting operation and predicting the crucial processing parameters, some of them being sometimes very difficult to be measured or calculated otherwise, e.g., temperature fields within the workpiece and the tool during the process. However, hard turning is a rather complex process, with cutting conditions that are different from conventional turning and, therefore it is desirable to take into account some special characteristics; for this purpose, the FEM programme Third Wave AdvantEdge, which is specially designed to simulate cutting operations, is used. For the simulation of hard turning both an orthogonal and an oblique cutting model are proposed.

2 Finite element modelling

Simulations of various machining operations using the finite element method have been reported over the last three decades; in References [9, 10] a collection of such papers can be found. The first models that appeared in the 1970s used the Eulerian formulation for modelling orthogonal cutting. In this approach the finite element mesh is spatially fixed and the material flows through it, in order to simulate the chip formation. The computational time in such models is reduced, due to the few elements required for modelling the workpiece and the chip, and it is mainly used for simulating the steady state condition of the cutting process. The elements do not undergo severe distortion, since the mesh is a priori known, but this formulation requires complex programming. Furthermore, experimental data must be on hand prior to the construction of the model in order to determine the chip geometry.

Although this formulation is still utilized by some researchers, the updated Lagrangian formulation has been proposed and is more widely used today. In this approach, the elements are attached to the material and the undeformed tool is advanced towards the workpiece. For the formation of the chip, a chip separation criterion in front of the tool edge is applied. There are many criteria proposed so far which can be geometric or physical and may involve for example a critical distance between the tool and the workpiece; when the tool reaches this critical distance from the workpiece the elements ahead of the tool edge are divided and thus the chip is formed. Other separation criteria pertain to critical values of e.g., stress or strain in order to initiate the chip formation and even crack propagation criteria have been reported for this procedure. A disadvantage of this method is connected to the large mesh deformation observed during the simulation; due to the attachment of the mesh on the workpiece material, the mesh is distorted because of the plastic deformation in the cutting zone. In order to overcome this disadvantage continuous remeshing and adaptive meshing are usually applied, increasing considerably the required calculation time. Nevertheless, the advances in computers have made it possible to reduce the time needed for such an analysis to acceptable levels. Note that an arbitrary Lagrangian-Eulerian formulation (ALE) has also been proposed with the aim of combining the advantages of the two methods, but it is not as widely used.

Most of the modelling work published so far pertains to 2D models of orthogonal cutting, while 3D models are rather rare in the relevant literature. That is mainly because, even though 3D cutting is more realistic, since cutting is 3D in nature, it requires a much more complex consideration of workpiece and cutting tool geometry, contact properties and, of course additional computational time. In particular, the work dedicated to hard turning is even more limited [11–15].

The models provided below are developed employing the Third Wave AdvantEdge software, which integrates special features appropriate for machining simulation. The programme menus are designed in such a way that they allow the user to minimize the model preparation time. Furthermore, it includes a wide database of workpiece and tool materials commonly used in cutting operations, offering all the required data for effective material modelling. The AdvantEdge code is a Lagrangian, explicit, dynamic code, which can perform coupled thermo-mechanical transient analysis. The program applies adaptive meshing and

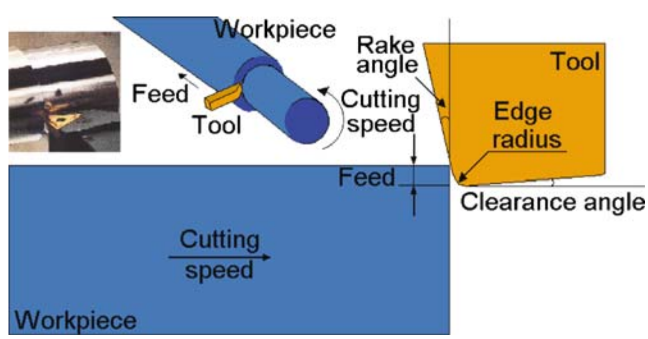

Fig. 1 Orthogonal cutting model schematic diagram

continuous remeshing for chip and workpiece, allowing for accurate results. For an analytical discussion on the numerical techniques used in the programme and a comprehensive presentation of its functions see Reference [16].

3 Results and discussion

3.1 Orthogonal cutting models

The orthogonal cutting schematic diagram used in the programme is shown in Fig. 1. The depth of cut is perpendicular to the plane shown in the figure and in the plane strain case, it is considered to be large in comparison to the feed.

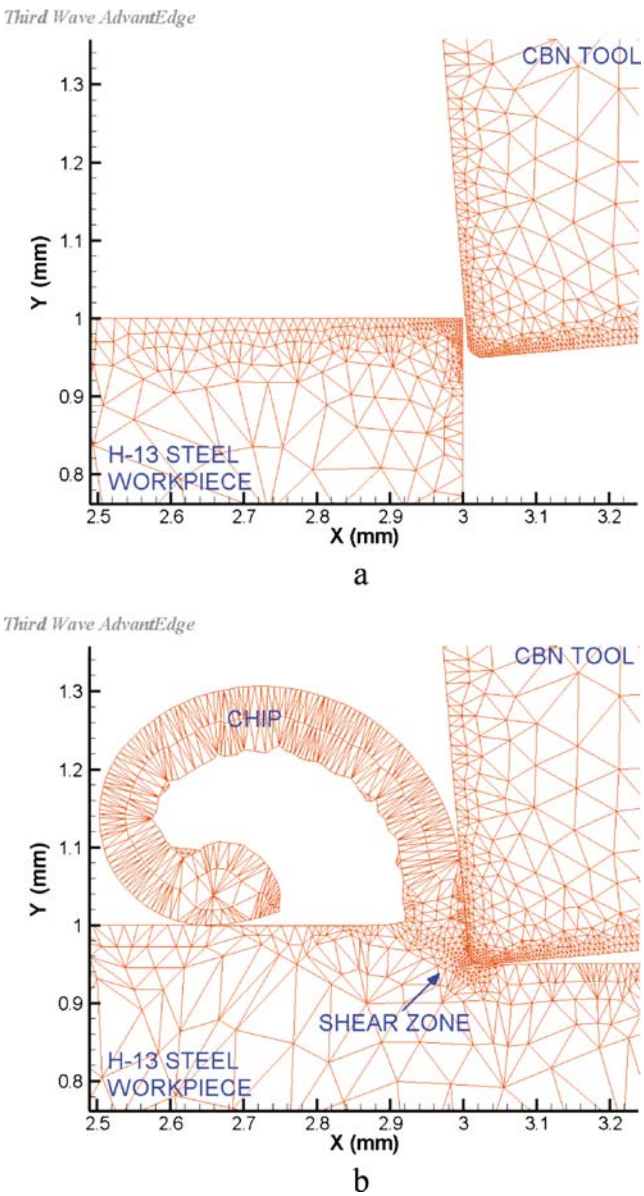

Fig. 2 (**a**) Initial mesh and (**b**) mesh at l=1.5 mm

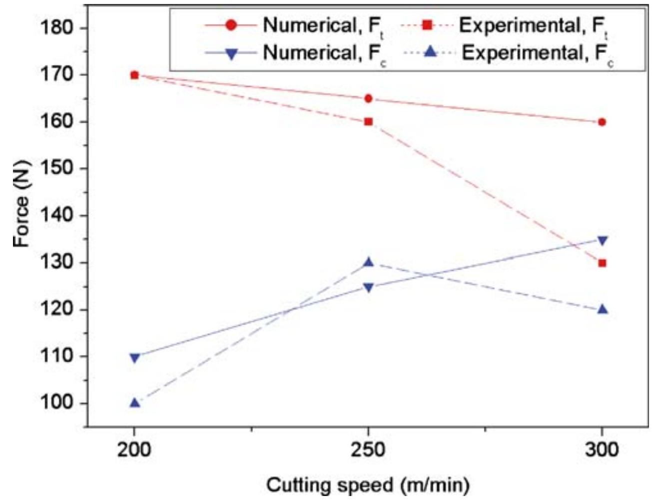

Fig. 3 Numerical and experimental results of thrust and cutting forces for three different cutting speeds

In the present analysis the workpiece material is the AISI H-13 hot work tool steel and its length is taken equal to l=3 mm. The tool material is CBN and the modelling of tool-chip interface friction is based on Coulomb's friction law, with friction coefficient set constant at the value μ=0.5. A cutting tool, with −5° rake angle, 5° clearance angle and 0.02 mm cutting edge radius, is used for the analysis. Furthermore, the feed is taken equal to f=0.05 mm/rev, while three different cutting speeds, namely v_c=200, 250 and 300 m/min, are considered. In Fig. 2(a) and (b) the initial mesh and a typical mesh created after the tool has cut half of the workpiece length (l=1.5 mm for time $t=3\times 10^{-4}$ s), for v_c=300 m/min respectively, are shown. In this figure, the continuous meshing and the adaptive remeshing procedures can be observed. Note, that, in Fig. 2(a) the mesh is denser near the tool tip, where deformation is about to take place, while in Fig. 2(b) new elements are created in the shear zone where the strain rate is expected to be high. Note, also, that the mesh density in the chip, especially in its inner and outer surfaces, is also high because of the deformation of the material in this area; finer mesh can follow the curve of the curling material more closely and, furthermore, provide more accurate results.

For the validation of the proposed hard turning model experimental results from the relevant literature are used, where the high speed turning of hard steel tubes (55 HR_C), in order to achieve orthogonal cutting conditions, is performed [17]. In Fig. 3 the experimental values of the thrust force F_t and the cutting force F_c are compared to the ones predicted from the models. From this figure it can be seen that the experimental and the numerical results are in a very good agreement and, generally, they follow the same trends; thrust force, which is the largest force component, decreases for increasing cutting speed, while cutting force increases slightly. Nevertheless, in almost all the cases, the

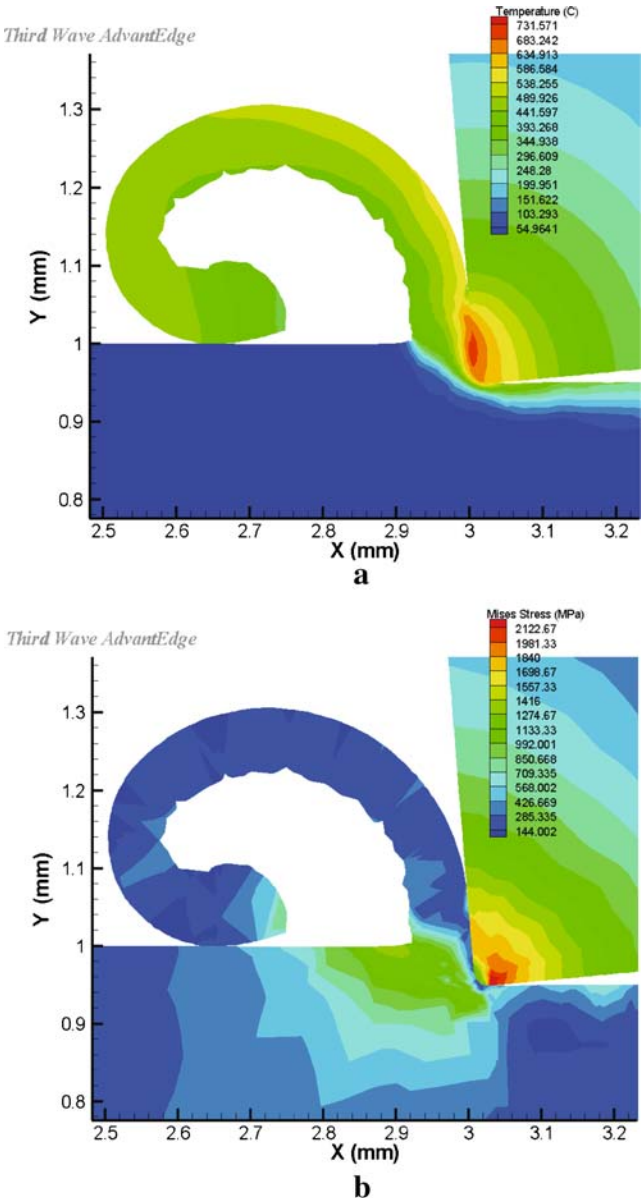

Fig. 4 (**a**) Temperature distribution and (**b**) von Mises stresses in the workpiece, the chip and the cutting tool

numerical values seem to overestimate the experimental ones while the discrepancies are larger for higher cutting speeds; this may be attributed to the large strain-rates developed during the process that alters the material behaviour in such a way that they cannot be taken into account by the model or to inadequate friction modelling, which means that a more advanced friction theory needs to be modelled.

Note, also, that it is possible, besides the cutting and thrust forces, to extract from the proposed model predictions for values that it would be very laborious or even impossible to obtain otherwise. Examples of such cases are: the temperature distribution in the workpiece and tool in the form of isothermal bands and the von Mises stresses developed during cutting. In Fig. 4(a) and (b) the temperature fields and the von Mises stresses, respectively, for cutting with v_c=300 m/min, are shown. These figures demonstrate the model at a step of the analysis, specifically for length of cut l=1.5 mm, where cutting is well into the steady-state region.

The form of the results is similar for all conditions, except of course the magnitude. From the results obtained, it may be concluded that the maximum temperature increases with increasing cutting speed, being 620°C, 690°C and 730°C for the three different cutting speeds considered. This may explain that the thrust force decreases for higher cutting speed, since softening of the material for higher temperature takes place. The regions that are mostly thermally loaded are the chip and the rake face of the tool, in the chip-tool interface close to tool tip, due to the plastic deformation of the chip and the frictional forces; the part of the chip that is curled away from the rake face is progressively cooled down. The stress has an almost constant value along the centre of the shear zone, while near the tool tip it has lower values; this can be explained due to the temperature rise of this area which softens the material.

The knowledge of the maximum temperature and of the distribution of the temperature fields in the rake face of the tool is of great interest because high temperatures in CBN tools are connected to wear mechanisms that reduce the tool life. With the numerical results provided by the model it is possible to minimize unwanted effects and to choose suitable cutting conditions in order to optimize the process.

Another option of the proposed orthogonal cutting model is to simulate the burr formation developed when the cutting tool exerts the full length of the workpiece; this can be achieved when the analysis is appropriately extended, so that the cutting path of the tool is longer than

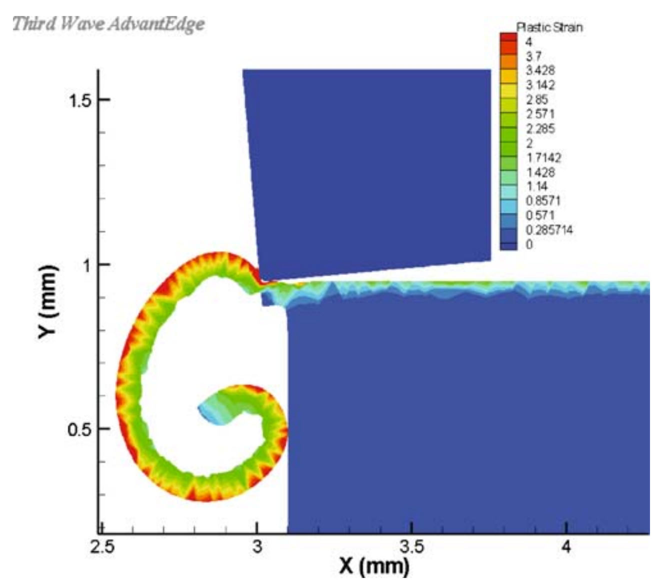

Fig. 5 Burr formation and plastic strain of the workpiece and the chip

the workpiece length. In Fig. 5 the burr formation in the workpiece and the plastic strain of the workpiece and the chip, for v_c=300 m/min, can be seen.

3.2 Oblique cutting models

The 2D models presented so far are more popular in the modelling of cutting operations since they are relatively simple and they can offer acceptable accuracy. Nevertheless, orthogonal machining is an ideal representation of cutting, where the chip deforms in a plane; in reality, chip deformation in turning takes place in all the three dimensions. The 3D models proposed so far in the literature are different from the classical oblique cutting model approach [14, 15]. However, it is this approach that will be presented in this work since much experience has already been accumulated from its application to similar problems, adequately handling 3D modelling with the finite element method. For the simulation the same software, as previously, is used. Furthermore, all the parameters of the workpiece and the cutting tool, as well as the cutting conditions are the same as in the models of the previous paragraph, for cutting speed v_c=300 m/min. Additionally, a back rake angle of 20^o is given to the tool.

The proposed oblique cutting model for dry high speed hard turning can provide, as in the case of 2D modelling, much useful data. In Fig. 6 the temperature fields in the workpiece, the chip and the tool can be observed. In the same figure, the position of the cutting tool, relative to the workpiece, can also be seen, explaining the form of the chip created. The curling of the chip can be better observed in Fig. 7, where a rear view of the workpiece in the same time step can be seen. Additionally, in the same figure, the cutting tool is omitted so that the temperatures at the location where cutting takes place can be observed.

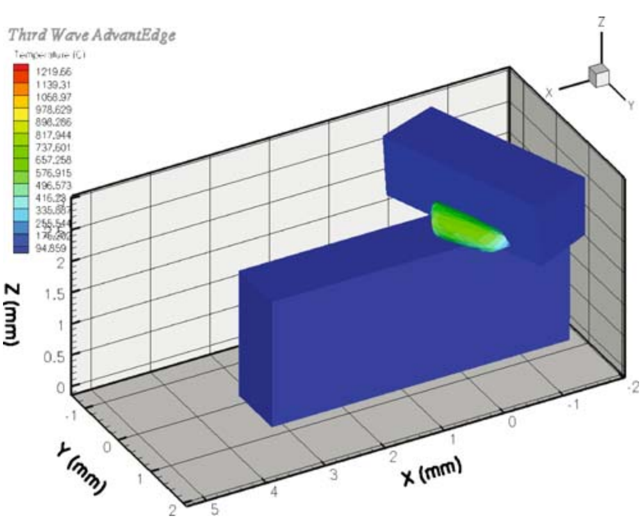

Fig. 6 Temperatures predicted by the oblique cutting model for hard turning

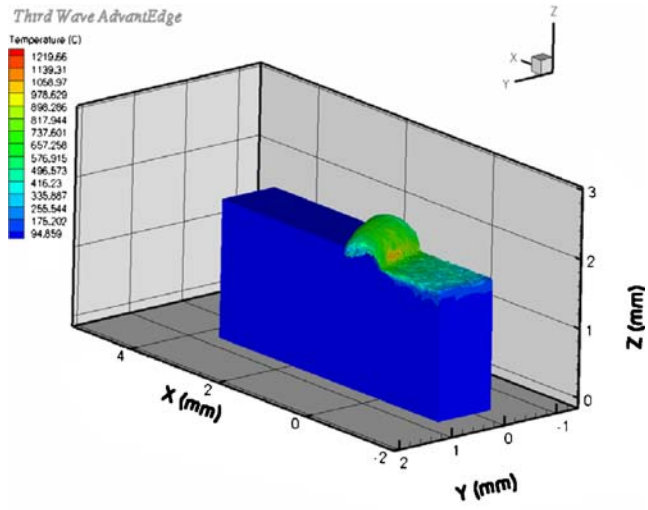

Fig. 7 Rear view of the model

Note that in these models more elements than the 2D models described so far are required, with computational time being approximately 10 times more; the computational time required for a 3D model on a moderate PC is over 100 hours. Even though 3D models provide more information being more realistic, they present this drawback that makes them less practical than 2D models.

4 Conclusions

Summarizing the results reported above, one may conclude that hard turning is considered to be a new machining process that has many advantages in comparison to other processes in the machining of hardened steels. Especially, when hard turning is performed at high speeds, it is even more advantageous, offering reduced machining time and cost characteristics.

The finite element method has been extensively used for modelling machining operations in the past. This method is also used in the present paper and the commercial FEM programme Third Wave AdvantEdge programme is employed. With the aid of this specialised software, simulation of 2D orthogonal cutting and 3D oblique cutting models are provided.

The orthogonal cutting models provide results such as cutting and thrust forces which were compared to experimental results from the relevant literature. However, other results such as the workpiece and tool temperatures, stress and strain can be predicted; these results would be very laborious and time consuming to be obtained otherwise. The latter results can be used for the theoretical study of the process as well as to be connected with certain phenomena appearing in this kind of machining such as tool wear which in turn affects workpiece surface integrity. Additionally, the burr formation in orthogonal cutting was modelled and presented.

The 3D oblique cutting models represent a situation were the chip deforms not in plane as in the ideal case of orthogonal cutting but in all three dimensions; a more realistic approach is, thus, provided. The proposed oblique cutting models are in a position of providing the same data as the 2D models, but also some additional information, e.g., for the 3D formation of the chip. Nevertheless, these models are more complicated and require the use of much more elements increasing this way the effort and the computational time required for the analysis.

From the analysis it can be concluded that the proposed models are practical, since only a minimum amount of experimental work is needed, and produce reliable results, allowing for industrial use in pursue of optimal production.

References

1. Trent EM, Wright PK (2000) Metal cutting, 4th edn. Butterworth-Heinemann, Woburn, MA, USA
2. Tönshoff HK, Arendt C, Ben Amor R (2000) Cutting of hardened steel. Annals of the CIRP 49/2:547–566
3. Byrne G, Scholta E (1993) Environmentally clean machining processes - a strategic approach. Annals of the CIRP 42/1:471–474
4. Klocke F, Eisenblätter G (1997) Dry cutting. Annals of the CIRP 46/2:519–526
5. Kundrák J, Mamalis AG, Gyáni K, Markopoulos A (2006) Environmentally friendly precision machining. Mater Manuf Process 21:29–37
6. Kundrák J, Mamalis AG, Markopoulos A (2004) Finishing of hardened boreholes: grinding or hard cutting? Mater Manuf Process 19/6:979–993
7. Knuefermann MMW, McKeown PA (2004) A model for surface roughness in ultraprecision hard turning. Annals of CIRP 53/1:99–102
8. Kishawy HA, Elbestawi MA (2001) Tool wear and surface integrity during high-speed turning of hardened steel with polycrystalline cubic boron nitride tools. Proc Instn Mech Engrs 215 Part B:755–767
9. Mackerle J (1999) Finite-element analysis and simulation of machining: a bibliography (1976–1996). J Mater Process Technol 86:17–44
10. Mackerle J (2003) Finite element analysis and simulation of machining: an addendum a bibliography (1996–2002). Int J Mach Tools Manuf 43:103–114
11. Ng E-G, Aspinwall DK, Brazil D, Monaghan J (1999) Modelling of temperature and forces when orthogonally machining hardened steel. Int J Mach Tools Manuf 39:885–903
12. Ng E-G, Aspinwall DK (2002) Modelling of hard part machining. J Mater Process Technol 127:222–229
13. Movahhedy MR, Altintas Y, Gadala MS (2002) Numerical analysis of metal cutting with chamfered and blunt tools. J Manuf Sci Eng - Transactions of the ASME 124:178–188
14. Guo YB, Liu CR (2002) 3D FEA modeling of hard turning. J Manuf Sci Eng - Transactions of the ASME 124:189–199
15. Klocke F, Kratz H (2005) Advanced tool edge geometry for high precision hard turning. Annals of CIRP 54/1:47–50
16. Marusich TD, Ortiz M (1995) Modelling and simulation of high speed machining. International Journal of Numerical Methods in Engineering 38:3675–3694
17. Özel T, Nadgir A (2002) Prediction of flank wear by using back propagation neural network modeling when cutting hardened H-13 steel with chamfered and honed CBN Tools. Int J Mach Tools Manuf 42:287–297